D and J/ψ production from deconfined matter in relativistic heavy ion collisions

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Abstract

We study the production of the D and J/ψ mesons from deconfined quark matter at CERN SPS energy. Using the MICOR microscopical coalescence model we determine the transverse momentum spectra of these charm mesons. We predict the slopes of their transverse momentum spectra in Pb+Pb collision at 158 GeV/nucleon beam energy.

During the last decade charm hadron production was investigated with great interest at the CERN Super Proton Synchrotron (SPS), because the theoretically predicted anomalous suppression of the J/ψ particle could indicate the appearance of colour deconfinement and the formation of the quark-gluon plasma (QGP) phase [1]. An anomalous suppression has been detected in Pb+Pb collisions at 158 GeV/nucleon bombarding energy [2] and this result is considered as the strongest evidence of QGP formation (for an overview see Ref. [3]). However, the unambiguous confirmation of the QGP formation requires more charm related data, e.g. D-meson spectra and absolute yields. This provides motivation to measure open charm production in Pb+Pb collision at the CERN SPS [4]. In parallel, new theoretical efforts work to determine charm hadron yields and ratios in this energy range using statistical [5], thermal [6] and non-equilibrium [7] models of charm hadron production.

Since momentum spectra could reveal some interesting details about the formation mechanisms of charm hadrons and thus the properties of the early (supposedly deconfined) phase, our aim is to determine the transverse momentum spectra of the D and J/ψ mesons in heavy ion collisions. We assume that hadrons are produced directly from a deconfined state by quark coalescence. We neglect hadronic rescatterings. This hadronization scenario is modelled using MIcroscopical COalescence Rehadronisation (MICOR) [8, 9, 10] which has been successfully applied to reproduce the measured transverse slopes of the ϕ, Ω and ρ mesons [8]. (The spectra of other light and strange hadrons were investigated previously in Refs. [9, 10].) The MICOR model is the successor of the ALCOR [11, 12] and the Transchemistry [13] models. While the ALCOR and Transchemistry models were constructed to determine the total number of hadrons produced from quark matter, the

MICOR model can also determine the full momentum spectra of the produced hadrons. We therefore include charm quarks into the MICOR model and calculate the spectra of directly produced charm mesons.

In the MICOR model we start with a deconfined initial phase as motivated by lattice QCD calculations. (Note that phase differs from the idealized, asymptotically free quark-gluon plasma [14].) The lattice results for the QCD equation of state (with $N_f = 0, 2, 4$ flavour) were parametrized phenomenologically as a massive quark matter [15]. This parametrization reproduces the lattice QCD results regarding the pressure and energy density in the temperature region $1 \leq T/T_c \leq 3$ [15] and thus it can be used as a suitable description of hadronization. The massive gluons (whose number is suppressed relative to the quarks and antiquarks) create an attractive effective force between the colored quarks and anti-quarks which drives the hadronization. According to our assumption, the quark matter here is a fully thermalized state, and in the hadronization stage is characterized by a hadronization temperature T_{had}, a transverse flow v_T^0 and a Bjorken-scaled longitudinal flow.

The coalescence of the massive quarks produces a hadron resonance gas, which is out of equilibrium [8]. This out of equilibrium character will not change during the resonance decay. While the final state hadronic spectra can be fitted by exponential functions on transverse momenta, this does not mean that the obtained slope parameters characterize equilibrated hadronic gas states.

During hadronization meson-like objects are formed via quark-antiquark coalescence (see Ref. [11] for the coalescence cross section), while baryon-like objects are formed in two steps: the formation of diquarks from quarks are followed by the coalescence of diquarks and quarks into baryons. We assume that color-neutral prehadrons escape the deconfined state without desintegration and that they become part of the produced excited hadronic gas. These prehadrons are off-shell, however their off-shell masses are very close to the well-known bare hadron masses. This minor difference is corrected in a last step of the hadronization, when a prehadron absorbs or radiates the appropriate (small) energy to become on-shell. We assume that it conserves its velocity during this process. More details about the physics of the MICOR model can be found in Ref. [8].

The initial condition of the MICOR hadronization model consists of the hadronization temperature, T_{had}, and the initial transverse flow, v_T^0, of the deconfined phase. The analysis of the measured transverse momentum spectra of ϕ, Ω and ρ particles was performed in Ref. [8] and fits to these experiment data favor initial values of $T_{had} = 175 \pm 15$ MeV and of $v_T^0 = 0.46 \pm 0.05$ in the Pb+Pb collision. We will use the mean values of these parameters to calculate charm meson production. The theoretical uncertainty of our calculation will be estimated through the uncertainty of these initial parameters. We consider a large enough longitudinal extension for the deconfined matter: $\eta_0 = \pm 2.2$, where η_0 is the space-time rapidity (this parameter will not influence the transverse momentum spectra at $y = 0$). The constituent quark masses are chosen to be $m_Q = 310$ MeV, $m_S = 430$ MeV, $m_C = 1540$ MeV.

We calculate the transverse momentum spectra of D and J/ψ mesons in Pb+Pb collision at $T_{had} = 175$ MeV and $v_T^0 = 0.46$. The D meson is produced from the coalescence of a charm quark and a $\overline{Q}$ antiquark, while the J/ψ is produced as a $C\overline{C}$ state. Figure 1 displays the obtained spectra with arbitrary normalization. The full line shows the

MICOR result and the dashed line indicates the best fit with the parametrization

$$dN/m_T dm_T = C \cdot m_T^{1/2} \exp(-m_T/T_{eff}) \tag{1}$$

in the momentum regions $0.3\ GeV < m_T - m_i < 2.2\ GeV$. In this region we obtain $T_{eff}^{Pb+Pb}(D) = 259$ MeV and $T_{eff}^{Pb+Pb}(J/\psi) = 315$ MeV for the effective slope parameters. Figure 1 shows how the non-thermal momentum distribution produced in the coalescence process (full curve) mimics the thermalized distribution of eq. (1) (dashed curve) in large momentum region.

The NA38 Collaboration has measured the transverse spectra of the J/ψ in S+U collision at 200 GeV/nucleon bombarding energy [16]. To apply our model, we assume that the massive quark-antiquark matter was already produced in S+U. In Figure 1 the experimental data from Ref. [16] are marked by full dots (at arbitrary normalization). The full curve is the MICOR calculation using $T_{had} = 175$ MeV and a reduced transverse flow, $v_T^0 = 0.33$. This reduced value for the transverse flow can be understood, since the smaller project radius of S+U collision yields a smaller transverse size and shorter expansion time for the deconfined phase as compared to that in the Pb+Pb collision. Using the parametrization of eq. (1) in the momentum region $0.3\ GeV < m_T - m_{J/\psi} < 2.2\ GeV$ we obtained $T_{eff}^{S+U}(J/\psi) = 234$ MeV (dashed line) thus recovered the experimental value, $\widehat{T}_{eff}^{S+U}(J/\psi) = 234 \pm 3$ MeV, obtained in the highest transverse energy bin (see Ref. [16]). (The published slope value was obtained with the fit $dN/m_T dm_T = C \cdot m_T \cdot K_1(m_T/T)$, which is approximately the same one as eq.(1) in the temperature region $T \approx 200 - 300$ MeV for particles heavier than the proton, see Ref. [8].) For the D-meson we obtain $T_{eff}^{S+U}(D) = 211$ MeV. Figure 1 shows the MICOR result (full line), while the fit from eq.(1) is indicated by dashed line.

We now investigate the dependence of the final transverse slope on the hadronization temperature and transverse velocity. First we fix the hadronization temperature at $T_{had} =$ 175 MeV and vary the transverse flow parameter, v_T^0. Figure 2 shows our predictions on the effective slopes for the J/ψ (upper curve) and for the D meson (lower curve) spectra. The open squares show the MICOR results in the Pb+Pb collision at 158 AGeV energy at $v_T^0 = 0.46$. The uncertainty in the transverse flow, $\Delta v_T^0 = \pm 0.05$, yields an errorbar on the theoretical predictions: $T_{eff}^{Pb+Pb}(D) = 259 \pm 19$ MeV, $T_{eff}^{Pb+Pb}(J/\psi) = 315 \pm 35$ MeV. The NA38 result on J/ψ in S+U collision is indicated by the star and open circles show the MICOR predictions at $v_T^0 = 0.33$. Assuming a 10 % uncertainty in the transverse flow, namely $\Delta v_T^0 = \pm 0.03$, we obtain the theoretical predictions: $T_{eff}^{S+U}(D) = 211 \pm 9$ MeV, $T_{eff}^{S+U}(J/\psi) = 234 \pm 13$ MeV. These uncertainties show the strong dependence of the charm hadron slopes on the transverse flow of the intermediate deconfined phase. As new experimental data will appear, analysis of Figure 2 can be used to determine the appropriate v_T^0 parameter for the MICOR model at the $T_{had} = 175$ MeV hadronization temperature.

We repeat this calculation also varying the hadronization temperature, T_{had}, with a $\Delta T_{had} = 15$ MeV. The obtained theoretical uncertainty remains in the same scale, ± 15 MeV.

In Figure 3, we display the MICOR results for the T_{eff} slopes of the D and J/ψ mesons produced in Pb+Pb collisions (they are marked with open squares). We also display the measured and the calculated slope parameters for the ρ, ϕ and Ω [8]. Experimental data

on the slope parameter of other particles are from Refs. [17, 18, 19, 20]. (All data was parametrized by eq. (1) in the momentum region $m_T - m_i > 0.3$ GeV.)

A similar plot can be created for the S+A collisions at 200 GeV/nucleon project energy. Figure 4. includes results for S+U [16], S+W [21, 22] and S+Au [23] collisions. The open squares show the MICOR results for particles ρ, ϕ, Ω, D and J/ψ. Here the J/ψ data determines the transverse flow parameter, $v_T^0 = 0.33$, which reproduce the slope for the ϕ meson.

Figures 3 and 4 support the assumption that the secondary hadronic interactions only slightly modify the transverse momentum spectra at higher momenta, $m_T - m_i > 0.3$. They reveal that the separation of the p^+, $\overline{p}^-$, Λ, $\overline{\Lambda}$, Ξ^- and $\overline{\Xi}^+$ from the weakly interacting ϕ and Ω is small. Even more, the slopes of the p^+ and $\overline{p}^-$ are very close to that of the weakly interacting ϕ meson. Thus we do not expect considerable modification of the much heavier charm mesons transverse spectra.

Our result sides with the analysis of hydrodynamical expansion versus hadronic cascade evolution performed by URQMD [25], where enhanced initial transverse flow was paired with a reduced influence of hadronic cascading in the transverse momentum spectra of heavier particle. In this manner, our result does not contradict to recent finding of Lin et al. [26], where relatively large modification was found from "hadron+D" collisions of the D-meson spectra in a longitudinally expanding system. Allowing a relatively large transverse flow, e.g. $v_T^0 = 0.46$ as in MICOR, the lifetime of the fireball will be shortened and the efficiency of the hadronic rescattering will be reduced.

In this paper, we predict the transverse slope of the D and J/ψ mesons in Pb+Pb collision at CERN SPS energy. Using the microscopical MICOR model we could follow the hadronization of the quark matter that we assume is produced in this heavy ion collision, and calculate the transverse momentum distributions. We obtained $T_{eff}^{Pb+Pb}(D) = 259 \pm 19$ MeV and $T_{eff}^{Pb+Pb}(J/\psi) = 315 \pm 35$ MeV. We compare our model with experimental data on J/ψ production in S+U collision and demonstrate that we can reproduce the measured spectra with a reasonably reduced transverse flow of the quark matter at a hadronization temperature of $T_{had} = 175$ MeV. We predicted the slope parameter of the D-meson to be $T_{eff}^{S+U}(D) = 211 \pm 9$ MeV. We urge future experiments to measure this quantity to provide further tests of this model.

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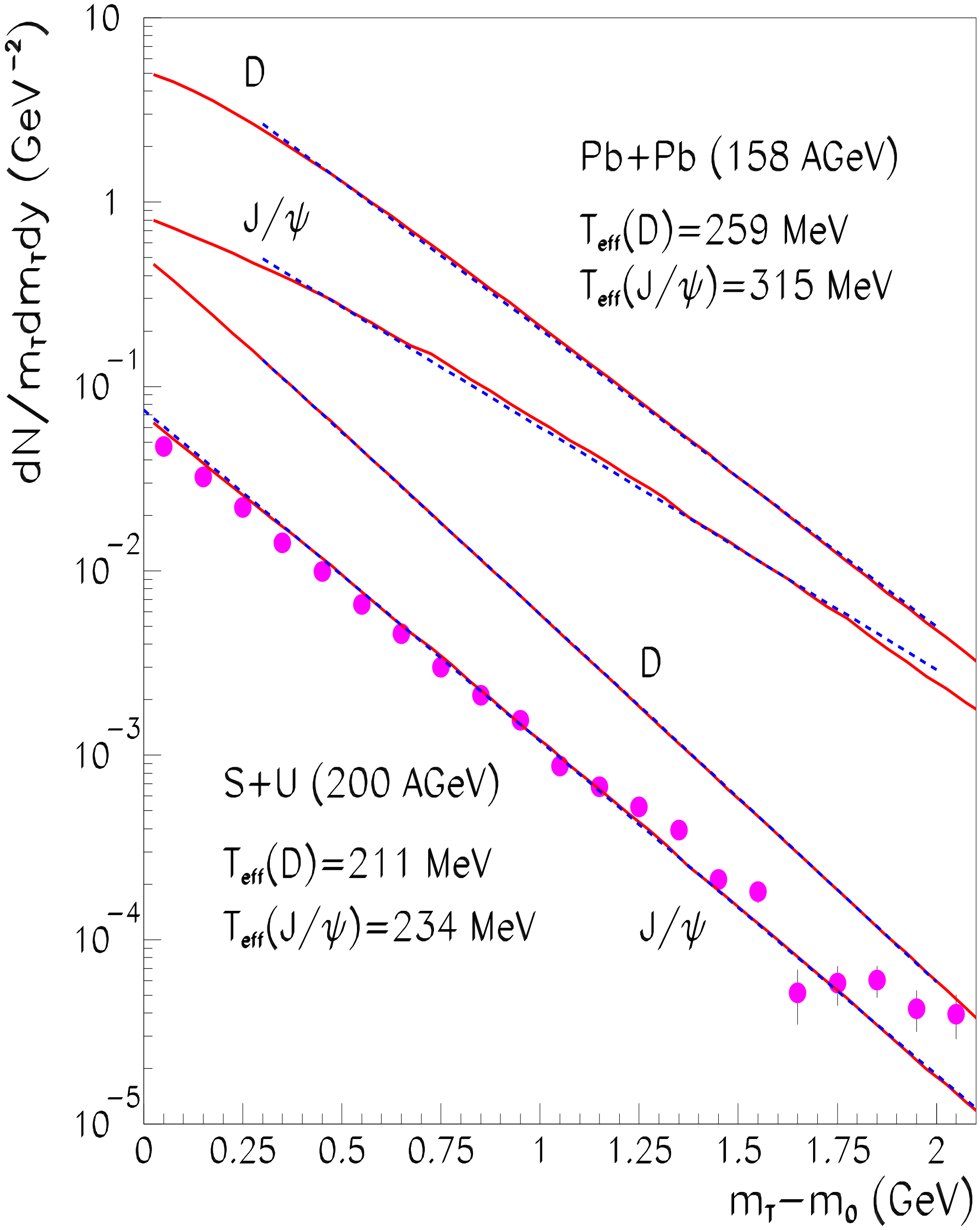

Fig. 1. The transverse momentum spectra of the D and J/ψ meson calculated by the MICOR model with parameters $T_{had} = 175$ MeV and $v_T^0 = 0.46$ for Pb+Pb collision at 158 AGeV and with $v_T^0 = 0.33$ for S+U collision at 200 AGeV (solid lines). The dashed lines are the fits of eq.(1) in the transverse momentum region $0.3 < m_T - m_i < 2.2$ GeV. The full dots are the data from the NA38 Collaboration for S+U collision [16].

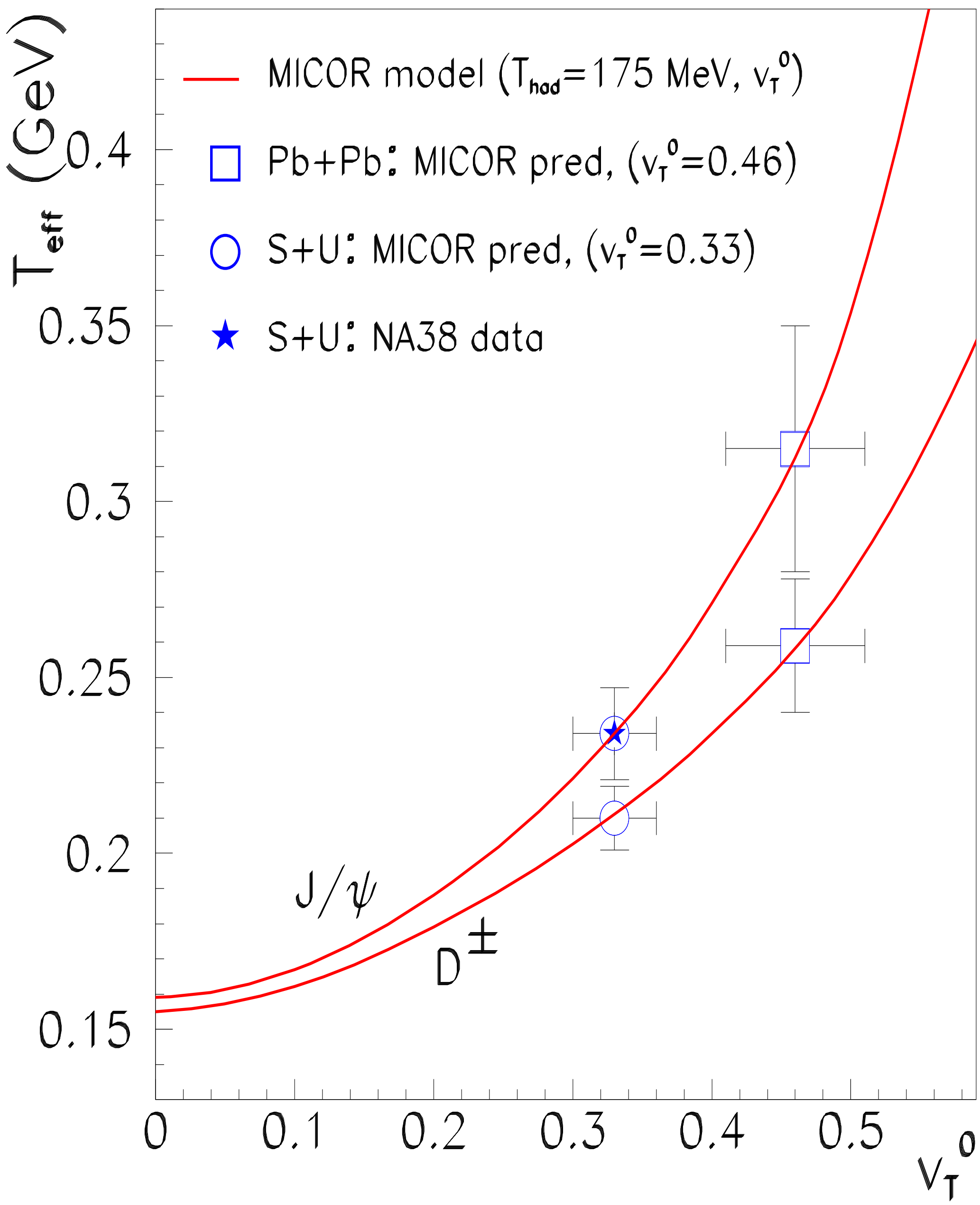

Fig. 2. Prediction from the MICOR model for the T_{eff} slopes of the D and J/ψ transverse momentum spectra as the function of initial flow v_T^0 at $T_{had} = 175$ MeV. The open squares indicate the MICOR prediction with $v_T^0 = 0.46$ for Pb+Pb collisions at 158 AGeV and the open circles indicate the prediction with $v_T^0 = 0.33$ for the S+U collisions at 200 AGeV. The errorbars shows the influence of 10 % uncertainty in the transverse flow. The star represents the NA38 experimental data for the J/ψ slope in S+U collisions, see Figure 1 and Ref. [16].

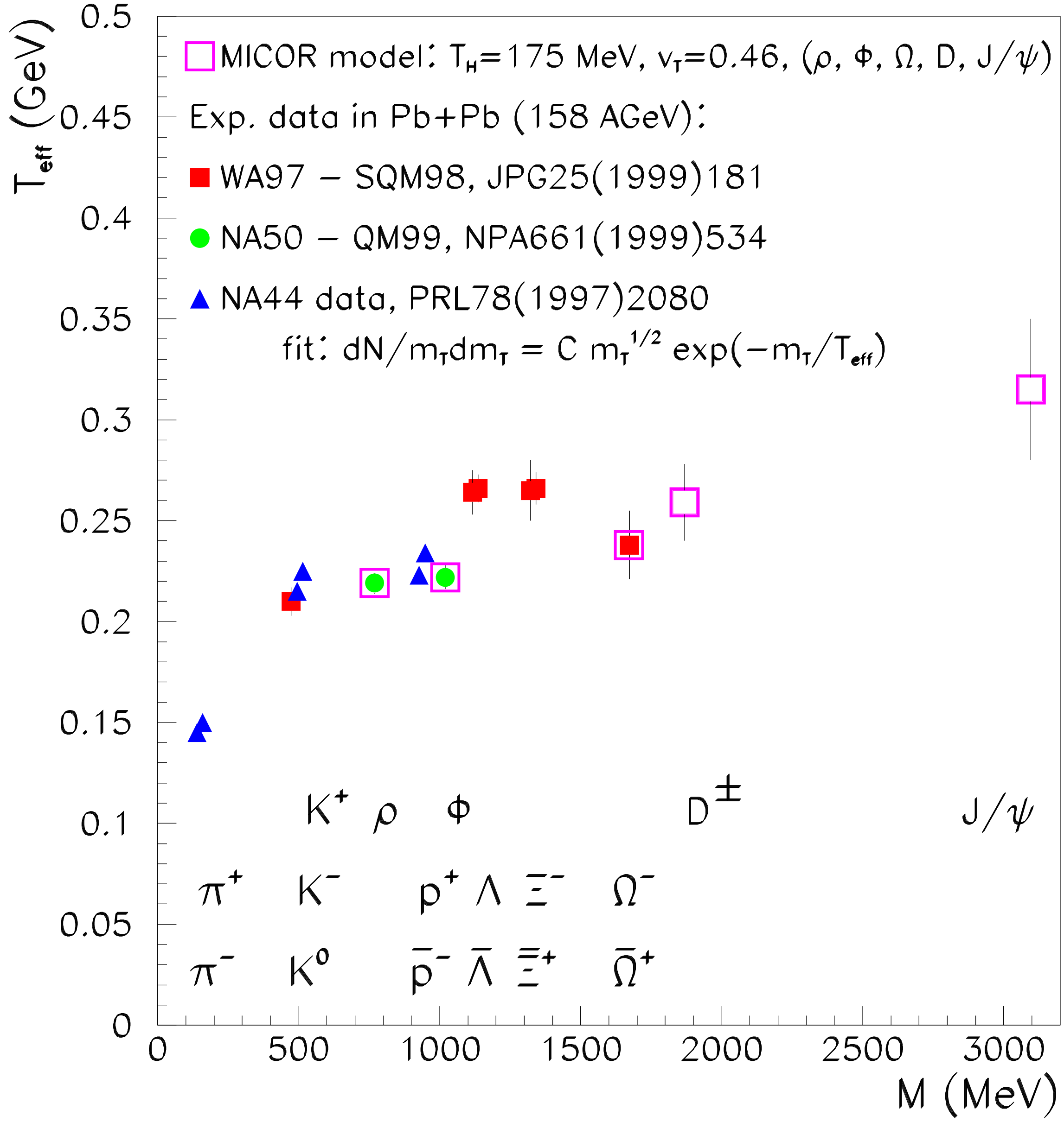

Fig. 3. Experimental hadronic slopes of the transverse momentum spectra in the PbPb collision at 158 AGeV energy from WA97 [17] (squares), NA50 [18] (dots) and NA44 Collaboration [19] (triangulars). The results of WA97 and NA50 were originally fit by eq.(1). We fit the NA44 data on $\pi^{\pm}$, $K^{\pm}$, p^{+} and $\overline{p}^{-}$ [19] in the same way in the momentum region $m_T - m_i > 0.3$ GeV. Open squares indicate the MICOR results on charm mesons and other hadrons.

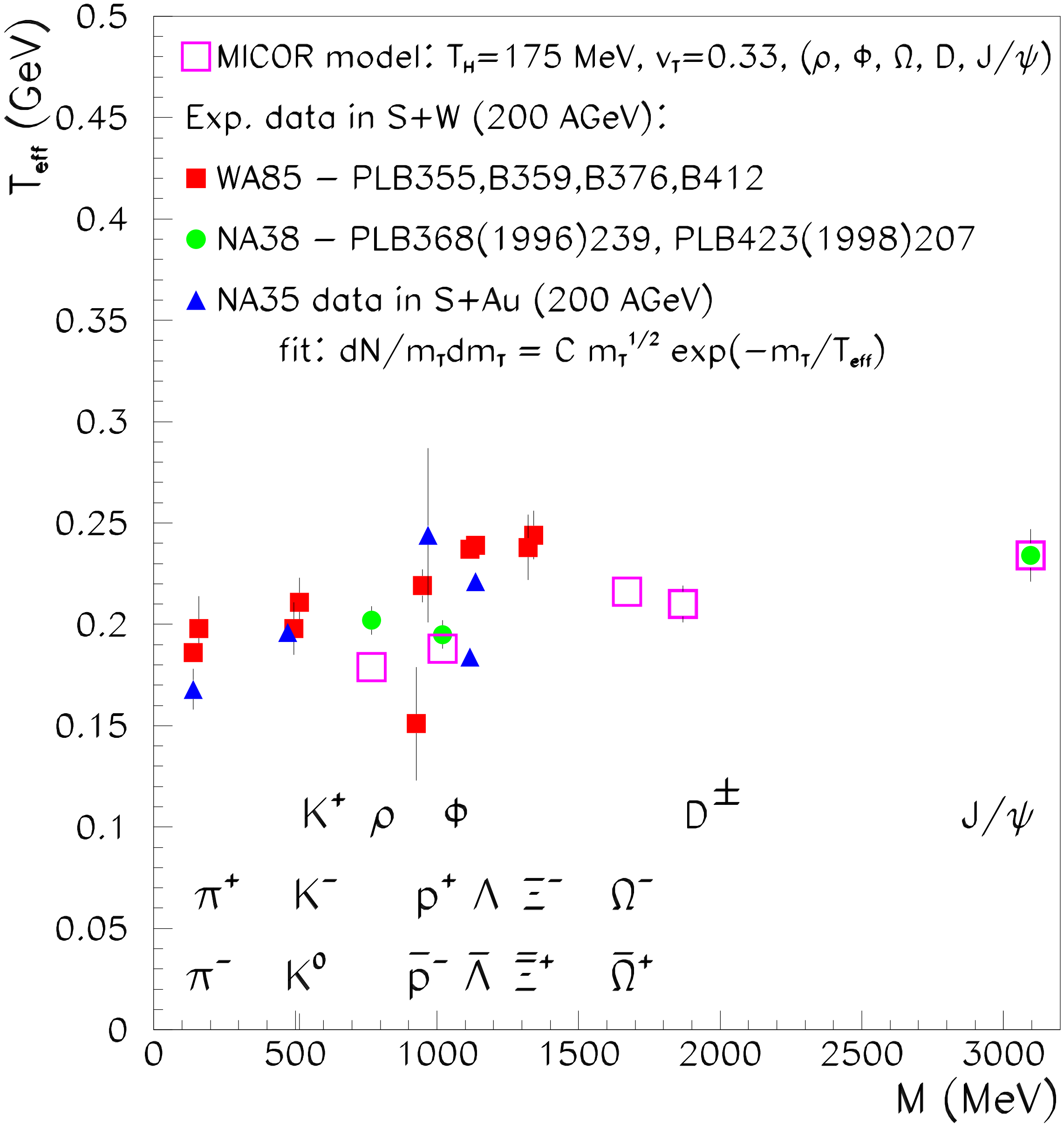

Fig. 4. Experimental hadronic slopes of the transverse momentum spectra in the S+W and S+Au collisions at 200 AGeV energy from WA85 [21, 22] (squares), NA38 [16, 24] (dots) and NA35 Collaboration [23] (triangulars). The results of WA85 and NA38 data were originally fit by eq.(1). We fit the NA35 data on π^-, K_S^0, p^+, Λ and $\overline{\Lambda}$ [23] in the same way in the momentum region $m_T - m_i > 0.3$ GeV. Open squares indicate the MICOR results on charm mesons and other hadrons.